

Atoll Mangrove Progradation Patterns: Analysis from Jaluit in the Marshall Islands

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Abstract

Low-lying islands are vulnerable to coastal erosion, and mangroves, which can mitigate erosion, have suffered enormous losses in recent decades owing to human impacts. Previous studies have little investigated mangrove shores on atolls, which may face combined multiple threats. We analysed the large Marshall Islands atoll of Jaluit, at a higher resolution than previous spatial change studies, finding that mangrove shorelines prograded seawards over the last seven decades. Biogeomorphic colonisation processes were characterised from transects along ~ 14.6 km of shorelines. Mangrove progradation occurred in patterns of arc-shapes evident of long-shore drift deposition, patch expansion of offshore mangrove colonisation showing the fastest rates of expansion. However, linear shoreline advance was the most frequent expansion pattern showing greater than three-fold more classified transects than arc-shaped colonisation and patch expansion. These results have implications for low island mangrove restoration. Applying mangrove planting patterns mimicking these different natural colonisation processes may enhance restoration success in ecosystem-based adaptation projects to mitigate sea level rise rates, and that rates of expansion vary according to patterns of biogeomorphic colonisation.

Keywords Pacific islands · Marshall Islands · Sea level rise · Mangroves · Atoll · Progradation patterns · Spatial change

Introduction

Island nations have extensive shorelines in proportion to their landmass; subsequently, their marine cultures and economies are predominantly on the coast (Kumar and Taylor 2015; Mimura and Nunn 1998; Nunn 2009; Mycoo et al. 2022). Low-lying islands, particularly atolls, are high-risk areas owing to changes in wave climate, El Niño Southern Oscillations (ENSO), extreme events and shoreline realignments that also influence erosion (Murray et al. 2003; Kumar and

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² School of Natural Sciences, Faculty of Science and Engineering, Macquarie University, Sydney, NSW 2109, Australia Taylor 2015; Mimura and Nunn 1998; Mycoo et al. 2022). Combined with relative sea level (RSL) rise, risks to communities may become intolerable (Kane and Fletcher 2020; Mycoo et al. 2022). These risks are combined with other climate change effects to threaten coastlines of many Small Island Developing States (SIDS) (Nunn 2009; Ford 2013; Storlazzi et al. 2015; Owen et al. 2016; Kane and Fletcher 2020; Nunn et al. 2021). Mangrove planting has become an adaptation action to increase coastal resilience for SIDS (Duarte et al. 2013; MyCoo et al. 2022), and better understanding of successful mangrove progradation on atolls could give insights to help success.

Mangroves are a significant coastal ecosystem in the tropical and sub-tropical SIDS (Bhattarai and Giri 2011; Moity et al. 2019). Mangrove coverage worldwide has been reduced from over 200,000 km² in the early twentieth century to 137,760 km² by 2000, indicating serious rates of loss (Giri et al. 2011). Losses have subsequently continued at reduced rates, mostly caused by direct anthropogenic drivers such as land conversion and human settlement expansion (Goldberg et al. 2020). Mangrove shorelines on atolls

provide benefits to people through protection from wave action during storms, sediment stabilisation (Ellison et al. 2017), and a range of services for human food security, including contributing to fish and invertebrate stocks (Lefcheck et al. 2019). These shorelines on atolls may be facing multiple threats from sea level rise (SLR) (Sasmito et al. 2016; Friess et al. 2022) as well as habitat losses (Giri et al. 2011; Goldberg et al. 2020).

Atolls have very low elevations and their islands are formed on sediments derived from coral reefs and ecosystem-associated molluscs, calcareous algae and foraminifera (McKee et al. 2007; Perry et al. 2011; Ellison et al. 2019; Kench et al. 2022). Atoll spatial change studies (Webb and Kench 2010; Rankey 2011; Ford and Kench 2015; Duvat 2019; Sengupta et al. 2021) have shown island loss and gain, spit rotation and extension and migration of islands on reef platforms. Spatial change analysis of 709 islands on 30 atolls across the Pacific and Indian Oceans over multi decadal timescales (Duvat 2019) showed that 73.1% of islands were stable in area, 15.5% increased, and 11.4% decreased in area. Beaches and spits showed marked changes over short and multidecadal timeframes, such as loss, contraction, rotation or extension. At low latitudes, multi-decadal spatial analysis of 104 islands from 16 atolls in the Federated States on Micronesia showed 46% of shorelines with statistically significant accretion (Sengupta et al. 2021). However, there has been inadequate analysis of spatial change of mangrove shorelines of atolls.

In Kiribati, the central Maiana atoll mangrove shore of 6 km length showed progradation of up to 83 m 1969–2009 (> 2 m/year) (Rankey 2011), with more than 5% of the 1969 sandy lagoon shoreline changed to mangrove shore by 2009. Also in Kiribati, the mangrove lagoon of the Nooto Ramsar Site on North Tarawa of 1 km in extent showed mangroves expanding and prograding seawards 1998–2013, increasing by 17%, at a rate of 604 m²/year (Ellison et al. 2017). In the Indian Ocean, 21 years of mangrove shoreline analysis on Aldabra showed mangroves to be mostly stable, with some loss to seaward and some mangrove migration inland (Constance et al. 2021). In the Marshall Islands, Jaluit mangrove shorelines showed progradation of up to 3 m/year between 1945 and 2019 (Crameri and Ellison 2022).

As part of a climate change vulnerability assessment of the largest mangrove atoll in the Republic of the Marshall Islands (RMI), spatial changes were analysed between 1945 and 2019 for inland and coastal mangroves (Crameri and Ellison 2022). Results from four continuous shorelines of larger islands showed progradation on the islands of Jaluit Jaluit (95.7% of transects), Medyai (100% of transects) and Aineman (88.5% and 94.6% of transects on shorelines designated Aineman 1 and 2, respectively). Jaluit Jaluit is the name used to describe the longest island located at the south of the atoll (Fig. 1) in Ramsar Site documentation (Bungitak 2003). Net shoreline movement of the prograding transects showed positive gains of up to 167.6 m, and of the prograding transects, with increased average shoreline distances of 44.4 m, 27.3 m, 6.1 m and 25.8 m respectively on Medyai, Jaluit Jaluit, Aineman 1 and Aineman 2. By contrast, average erosional distances were respectively 8.8 m, 8.6 m and 7.7 m at Aineman 1, Aineman 2 and Jaluit Jaluit. The aim of this follow-up study is to investigate patterns of biogeomorphic colonisation evident in shoreline progradation, such as patterns described from spatial analysis of Guiana coastlines (Fromard et al. 2004; De Jong et al. 2021) and Vietnam (Nardin et al. 2016):

- 1. Arc-shaped colonisation (ASC), where mangroves colonise sediment transported in an alongshore direction to form elongated bars or spits offshore,
- 2. Spatial expansion of colonising mangroves, to form offshore expanding knobs, separated by indentations of reduced or no expansion, termed patch expansion (PE),
- 3. Linear shoreline advance (LSA), with new mangrove zones forming seawards and parallel to the coastline.

We hypothesised that these different progradation types lead to mangrove expansion at different rates, and that some may be more prevalent than others. If this were the case for natural mangrove expansion on Jaluit Atoll, prevalent progradation patterns may be usefully applied to mangrove ecosystem-based adaptation elsewhere.

Methods

Study Area

Jaluit Atoll (Fig. 1) (6.05° N; 169.35° E) is part of the Ralik Island Chain in RMI and is composed of 91 islands (Ford and Kench 2016; Kench et al. 2022). It is located ~ 200 km southwest of Majuro, the capital of the RMI. The atoll is ~ 60 km by ~ 34 km with the vast majority of the atoll area of 689.74 km² being lagoon, and land area of only 11.34 km² (Ford and Kench 2016; Kench et al. 2022).

Jaluit is elongated north-south with more land on the eastern reefs of the atoll. Shoreline mangroves occur largely on the western lagoon side of these larger eastern islands, which with prevailing north-east trade winds would be lowest energy shores across the atoll. In these settings, records of indigenous mangrove species include *Rhizophora apiculata*, *Sonneratia alba* and *Bruguira gymnorrhiza* (Fosberg and Sachet 1962; Vander Velde and Vander Velde 2005).

Being located close to the equator, typhoons are rare in the southern Marshall Islands. Only two with geomorphic impact are recorded in 1905 and 1958 (Ford and Kench 2016), and our searches found no other records of storms.



Fig. 1 Map of Jaluit Atoll, showing locations of mangrove shorelines and study sites

Typhoon Ophelia in 1958 caused devastating effects to the island morphology and vegetation (Blumenstock 1958; Blumenstock et al. 1961). Erosional scouring of islands caused reduction in areas, major damage to vegetation, and new deposition of sediments created beach ridges and reef rubble bars (Blumenstock 1958; Ford and Kench 2016). The eastern reef islands of Jaluit Jaluit and Majetto were most impacted, with 70–90% of trees uprooted or broken below their crowns (Blumenstock 1958; Ford and Kench 2016). Vegetation on Jaluit soon recovered, and a survey 2 years later showed herbaceous and shrubby vegetation replacing barren areas, along with mangrove recovery (Blumenstock et al. 1961). Ford and Kench (2016) reported a 5.1% reduction in the total land area of the atoll between 1945 and 1976, analysing a portion of the same imagery as this study.

Jaluit's mangroves are protected under the RMI's National Conservation Area Plan (Reimaanlok), which develops community-based conservation management plans with support from a national expert team (Baker et al. 2011; Sterling et al. 2017). Unlike other atolls in the RMI, ownership on Jaluit includes coastal areas and lagoons as well as land (Lindsay and Aiello 2003), and decisions on resource use are made through traditional hierarchical systems primarily at the local level (Beger et al. 2008; Office of Environmental Planning Policy Coordination 2017). Furthermore, the Jaluit Atoll Marine Conservation Area was established in 1999 through the South Pacific Biodiversity Conservation Program (Bungitak and Lindsay 2004), and Jaluit was also designated as the first Ramsar Wetland of International Importance in RMI, with resources devoted to its conservation. As a Ramsar site, Jaluit has management plans that are managed by local government with support from the EPA office of RMI (Office of Environmental Planning Policy Coordination 2017).

Historical Imagery

Shorelines with mangroves were identified using ArcGIS (Version 10.8), analysing available imagery from Jaluit Atoll (6.05° N; 169.35° E). High spatial resolution photographs from 1945 allowed mangrove patches to be identified, avoid-ing limitations of low-resolution earlier imagery (Ruiz-Luna et al. 2010). The next timestamp was 1976 aerial photography obtained courtesy of the U.S. Geological Survey (2022). From 2010/2011, a DigitalGlobe image mosaic was available, and from 2018/2019, a Maxar satellite imagery had spatial resolution of between 0.64 and 0.21 m/pixel and limited cloud cover (Crameri and Ellison 2022). Atoll nations in the Pacific have limited aerial imagery available; hence, high-quality imagery up to 7 decades old is valuable in a region of generally sparse environmental data (Ford and

Kench 2015). Further information on the imagery used is provided in Table S1.

The historical imagery (1945, 1976, 2010/11) were overlaid and georeferenced to the 2018/2019 base imagery using fixed structures such as buildings, slipway edges and rock outcrops, as used by previous atoll spatial change studies (Ford 2013; Giri et al. 2011; Yates et al. 2013). Imagery from 1945 was not available across all analysed shorelines, and for some transects, mangroves were not present in 1945, in which case different image endpoints were reported for some transects. All shorelines analysed during this study were located on the lagoon shore of the islands (Fig. 1), this being the sheltered shoreline favouring mangrove habitats. The shoreline extents were all drawn using the same scale of 1:2,000 by the same individual for consistency. Atoll mangrove shorelines identified and mapped follow definitions previously used of 'mangrove forest' shorelines on Kiribati atolls of Maiana and Aranuka (Rankey 2011).

Shoreline Change Analysis

The shoreline change analysis was determined using the Digital Shoreline Analysis System (DSAS) version 5.0 add-in to Esri ArcGIS desktop (Himmelstoss et al. 2018). Further details on the DSAS methodology are provided in Crameri and Ellison (2022). Each shoreline transect was classified into the expansion categories based on their evident dominant colonisation process across each of the four shoreline timestamps, as modelled in Fig. 2. Where transects showed two classification types across the shoreline growth period, the overall category was determined by the classification type which measured the greatest increase in shoreline progradation.

DSAS analysis was conducted on 5.0-m spaced transects, using far closer transect spacing than previous studies (Ellison and Zouh 2012; Ford 2013; Ford and Kench 2015; Kench et al. 2018; Himmelstoss et al. 2018; Sengupta et al. 2021), allowing detailed analysis across the atoll islands.

Three rate-of-change statistics were calculated: linear regression rate, end point rate and net shoreline movement (Himmelstoss et al. 2018). Both end point rate and net shoreline movement require only two temporal shoreline positions, as opposed to three for linear regression rate, and as a result, both have a greater number of measured transects.

End point rate and net shoreline movement were both reported to enable better spatial and temporal context for the expansion of the mangroves. An annual rate of change, provided by the end point rate, may be more comprehensible to restoration practitioners compared to shoreline movement across more than 7 decades. However, the net shoreline movement provides a long-term view important for the state of mangroves on Jaluit regarding SLR. Linear regression rate also provides and annual rate, but it represents a more statistical approach compared to the end point Fig. 2 Model of mangrove expansion characteristics across Jaluit Atoll, **A** Arc shaped colonisation (ASC); **B** Colonisation by linear shoreline advance (LSA), and **C** Colonisation by patch expansion (PE)



rate, which can ignore data such as shorelines between the youngest and oldest shorelines (Himmelstoss et al. 2018). Further information for each method can be found in Himmelstoss et al. (2018).

Statistical Analysis of Shoreline Expansion Categories

Violin plots were created to display the variation in progradation/erosional context for each of the colonisation categories, using the 'ggstatplot' R package (Patil 2021; R Core Team 2018). Statistical analysis was conducted on the results of the three calculated DSAS shoreline statistics for each of the shoreline expansion categories. As the dataset did not meet the ANOVA assumptions for the homogeneity of variance and normality, a non-parametric Kruskal–Wallis rank sum test was used to assess whether differences between the three shoreline expansion categories were significant in each of the DSAS shoreline statistics. The post hoc Dunn test, adjusted with the Holm method to counteract multiple comparisons, was then used to assess between-group differences between each of the mangrove expansion categories. All static or eroding transects were removed from the shoreline expansion analysis, as the purpose of the study was to assess progradation patterns and not the overall change in shorelines.

Sea level trends were analysed combining two tide gauge datasets for Majuro, Majuro B (1968 to 1999) and Majuro C (1993 to 2019). Monthly tide gauge data were retrieved from the Permanent Service for Mean Sea Level (Holgate et al. 2013; NOAA 2021) from this nearest tide gauge, approximately 200 km away.

The mean rate of progradation was also calculated between each time stamp to provide an indication of how the shorelines behaved between each timestamp. This provided three periods of progradation: 1945–1976, 1976–2010/2011 and 2010/2011–2018/2019. All transects used in the original shoreline analysis were used, including static and eroding transects, to determine this rate between timestamps. Results of the analysis are reported using end point rate (m/year). All data and trend analysis were undertaken using Rstudio (R Core Team 2018).

Results

Spatial change of coastal mangroves from 14.6 km of mangrove coasts (Fig. 1) included 0.3 km on Medyai, 12.6 km on Jalueit Jaluit, 0.5 km on Aineman 1 (south part of the island) and 1.2 km on Aineman 2 (further north on the island) (Figs. S1–S17). DSAS measured 2922 transects of mangrove seaward edge change 1945–2018/2019, the sample number determined by mangrove shoreline length visible in available imagery and the 5.0 m transect spacing used.

Occurrences of different colonisation patterns showed ASC (Figs. 2A and 4A), where offshore sediment bars or spits were rapidly colonised by mangroves to close off lagoonal portions of the coastline to the ocean. Patterns also showed PE of offshore colonising mangroves (Figs. 2C and 4C), with examples evident mainly on Jaluit Jaluit (Figs. S8B, S10B north, S11B, and S15B). LSA parallel to the coastline was the most frequently occurring pattern (Table 1) (Figs. 2B and 4B), with greater than three times the numbers of transects of this type compared the other

prograding patterns (Table 1). LSA was the dominant form of colonisation following the disturbance caused by the 1958 Typhoon. Examples are evident on Medyai (Fig S2) where rates slow down over time, Aineman 1 (Fig. S4), and south Jaluit Jaluit (Fig. S7B) where rates also slow over the same timeframes.

Rates of expansion showed differing results to occurrence (Table 1), with ASC shown to have the greatest rate of progradation of each shoreline expansion statistic (1.11 m/ year linear regression rate). Lower rates of expansion were reported for PE and then LSA (0.48 and 0.33 m/year linear regression rate respectively). Results of the Kruskal-Wallis tests applied to the different progradation patterns indicated statistically significant variability between groups (Figs. 3 and S18). Significant differences were also found when comparing each pair of groups (ASC ~ LSA, ASC ~ PE, and PE~LSA) using the post hoc Dunn test, adjusted with the Holm method. The results of these multiple comparisons tests (Table 2) indicate that ASC showed statistically greater rates of progradation for each rate-of-change statistic. This was followed by PE, and then LSA showed the slowest rates of progradation.

Violin plots of net shoreline movement, linear regression rate and end point rate show distributions of the measured transects for the three different expansion types across analysed shorelines (Fig. 3; Fig. S18), useful to demonstrate distributions for the large data sets and to show variable density. In the plots, red dots indicate the mean, bars show interquartile range, the width of the curve shows frequency of data points for different linear regression rate/net shoreline movement magnitudes, and whiskers show the outer distribution with outliers. Skew from the median is towards greater progradation for each of ASC, PE and LSA, with ASC having the greatest median progradation and also the greatest range. PE and LSA types show lesser rates of movement or shoreline increase, and therefore greater stability.

The differing total numbers of transects (Table 1) are due to some sections of the shorelines, particularly along Jaluit Jaluit and Medyai shorelines, missing imagery and/or periodically did not have mangrove shorelines, especially during 1945 timestamp. Also, the numbers of transects differ for

 Table 1
 Transect results from the lagoon shoreline mangroves of Jaluit Atoll, Marshall Islands, of progradation categorised according to colonisation pattern: ASC (arc shaped colonisation), LSA (linear shoreline advance), and PE (patch expansion)

Change statistic	Shoreline change	ASC	LSA	PE
End point rate $(n=2720)$	Prograding (%)	497 (18.3%)	1,699 (62.5%)	524 (19.3%)
	Mean increase $(m/year \pm sd)$	0.99 ± 0.68	0.32 ± 0.27	0.47 ± 0.33
Net shoreline movement $(n=2731)$	Prograding (%)	497 (18.2%)	1,710 (62.6%)	524 (19.2%)
	Mean increase $(m \pm sd)$	64.5 ± 43.3	16.4 ± 12.8	26.2 ± 16.4
Linear regression rate $(n = 2536)$	Prograding (%)	480 (18.9%)	1,579 (62.3%)	477 (18.8%)
	Mean increase $(m/year \pm sd)$	1.11 ± 0.77	0.33 ± 0.28	0.48 ± 0.31





Fig. 3 Violin plots indicating the distribution of transects categorised by different expansion categories. **A** linear regression rate significant differences between groups (Kruskal–Wallis χ^2 =534.7, *df*=2, $p \le 0.001$); **B** net shoreline movement indicated significant differ-

 $p \le 0.001$); **B** net shoreline movement indicated significant differend point rate and net shoreline movement (n = 2720 and elsewhere in the Mars 2731 in Table 1), as in this analysis we removed the static results, with a mix of e

2731 in Table 1), as in this analysis we removed the static and eroding transects, being focussed on analysis of the progradation patterns. EPR is naturally going to be a lower number than NSM, and in some cases (11 transects in total), the EPR was rounded down to zero while the NSM remained above zero and hence was included in the analysis.

RSL data analysed from long-term tide gauges 1968–2018 on Majuro (Holgate et al. 2013; NOAA 2021), 200 km distant from Jaluit, indicated rising trends of 3.53 ± 1.8 mm per year (mm/year) (Fig. 5).

Discussion

Spatial Changes and Context in the Pacific

Mangrove shorelines on low energy coastlines of Jaluit Atoll showed extensive progradation across 14.6 km, concurring with smaller-scale atoll studies finding mangrove progradation (Rankey 2011; Ellison et al. 2017; Constance et al. 2021). Spatial analysis of non-mangrove shorelines

ences between groups (Kruskal–Wallis $\chi^2 = 717.8$, df = 2, $p \le 0.001$). End point rate results (Fig. S18) also indicated significant differences between groups (Kruskal–Wallis $\chi^2 = 537.2$, df = 2, $p \le 0.001$)

elsewhere in the Marshall Islands has shown dynamic results, with a mix of erosion and accretion (Ford 2013; Ford and Kench 2016). Wotje Atoll showed accretion to be dominant 1945 to 2010, then noteworthy erosion 2004 to 2012, with elongated spits the most dynamic (Ford 2013). Analysis of non-mangrove shorelines across six atolls in the Marshalls (Ford and Kench 2015) showed mostly accretion between the 1970s and 2010, followed by a slowdown. For Jaluit mangrove shorelines, while variation occurred between transects, average rates of progradation (Fig. 6) were greatest between 1976 to 2010/2011, corresponding with progradation of other atolls (Ford and Kench 2015). Rates then decreased between 2010/2011 and 2018/2019. These trends are exemplified by an increase in mangrove extent between 1976 and 2010 in Fig. 4A, but a much more limited increase between the other time stamps. Analysis of trends from the Majuro tide gauge (Fig. 5) shows several low sea-level years in the high progradation period (Fig. 6), which may have contributed.

Although results show overall progradation across the entire study period, limited temporal scale satellite and aerial imagery availability for Jaluit may mask shorter scale

Table 2Results of post hocDunn multiple comparison test,p values are adjusted using theHolm method

Colonization category comparison	End point rate		Net shore	Net shoreline movement		Linear regression rate	
	Ζ	p value	Ζ	p value	Z	p value	
ASC~LSA	22.52	< 0.001	25.97	< 0.001	22.53	< 0.001	
ASC~PE	9.93	< 0.001	11.28	< 0.001	9.82	< 0.001	
PE~LSA	10.54	< 0.001	12.37	< 0.001	10.32	< 0.001	



Fig. 4 Examples of mangrove expansion characteristics across Jaluit Atoll: A Shoreline dominated by arc shaped colonisation (ASC), background imagery from 12 Dec 2018; B Shoreline dominated by linear

shoreline advance (LSA), background imagery dated 07 Jan 2018; C Shoreline dominated by patch expansion (PE), background imagery dated 12 Dec 2018



Fig. 5 Majuro Atoll sea level trends with 95% confidence interval (NOAA 2021), adapted from Crameri and Ellison (2022)

oscillations/cycles in spatial trends of mangroves across the atoll. To gain improved understanding of the mangrove shorelines across these atoll environments, future analysis across years rather than decades would show better detail of changes along with ground survey. Ground survey could include shore-normal transects of plots quantifying mangrove species height, biomass, condition (Ellison et al. 2012), and accretion rates (Cahoon 2015) to better understand mangrove changes.

Over the last few decades, atoll islands have shown stability and accretion as well as some loss of island area

(Webb and Kench 2010; Rankey 2011), but no widespread sign of physical destabilization during sea-level rise (Ford and Kench 2015; Duvat 2019). Rates of change were not correlated with SLR rates, and more influenced by other climate drivers and human disturbances (Duvat 2019). These existing studies have focussed on non-mangrove shorelines of atolls such as beaches, and with mangroves globally under threat from mainly non-climate causes (Giri et al. 2011; Goldberg et al. 2020), so analysis of mangrovedominated atoll shorelines was a gap. Results from this study (Tables 1 and 2; Fig. 3) demonstrate atoll mangrove



Fig. 6 Rates of progradation across the three periods between time stamps; error bars indicate standard deviation

shoreline resilience during SLR (Fig. 5) with prevalent progradation evident, and with biogeomorphic processes differing (Fig. 2).

This progradation lagoon-wards of mangrove shores on Jaluit occurred despite RSL rise measured at the nearby Majuro Atoll $(3.53 \pm 1.8 \text{ mm/year})$, which is higher than global averages from tide gauge and satellite altimetry records of 2.06 [2.79–3.31] mm/year between 1970 and 2015 (Oppenheimer et al. 2019). Patterns of mangrove progradation during these conditions are needed to be understood to enable management of atoll mangrove resilience during projected future SLR.

Biogeomorphological Patterns

Previous observations of patterns in mangrove progradation have been from deltaic shorelines with large riverine sediment supplies (Fromard et al. 2004; Nardin et al. 2016; De Jong et al. 2021), yet similar patterns occurred on Jaluit's contrasting atoll shoreline (Figs. 2 and 4). This Jaluit study quantified differing rates of expansion of each progradation pattern, not analysed previously, and differences were shown to be significant (Table 2).

Prevalent mangrove colonisation patterns on Jaluit showed that the most frequent and spatially prevalent category was the LSA type, occurring in 62% of progradation transects (Table 1; Fig. 3). Resembling zonation advance (Figs. 2B and 4B), with bands parallel to the shoreline, in Guiana, this pattern occurred at the seaward edge, associated with increasing basal area, tree diameter, stand height, above ground biomass, and tree species diversity (Fromard et al. 2004; De Jong et al. 2021). Linear expansion was found also to be prevalent at seaward edges on the Mekong Delta (Nardin et al. 2016), triggered by high sediment availability and featuring increasing density. This pattern is also evident from Kiribati (Ellison et al. 2017), involving only *Rhizophora*, likely also to be the case on Jaluit. Possible factors encouraging LSA include sediment availability and deterministic biogenic processes (Ellison 2019) promoted by mangrove density.

Patch expansion (Figs. 2C and 4C) showed both a higher median and interquartile range relative to LSA (Fig. 3) but a lower occurrence across transects (Table 1). On Jaluit, PE occurred following Typhoon Ophelia at the seaward edge, and patterns of change suggested PE following local groundwater outflows indicated by darker offshore benthic colours (Fig. 4C). On deltaic shorelines PE rather occurred at finer scales with slower expansion expanding both seaward and internally to the swamp (Fromard et al. 2004; Nardin et al. 2016; De Jong et al. 2021). From Kiribati, seaward patch expansion is also evident 1998–2013 (Ellison et al. 2017) associated with increasing density of *Rhizophora stylosa*. Possible factors encouraging PE include groundwater outflow, root mat accretion, and increasing tree density causing increased retention of sediment.

Arc shaped colonisation (Figs. 2A and 4A) showed the most rapid mangrove progradation rates but the least occurrence across transects (Table 1), with the greatest median and interguartile ranges of net shoreline movement (Fig. 3) of all patterns. Spit extension occurred parallel to the island shoreline in the largest cases, the largest example on Jaluit Jaluit (Fig. S13) from north to south, indicating influence of the prevailing north-east trade winds. Other arc-shaped expansions were from north to south (Fig. S12), south to north (Figs. S14B and S16B) and west to east (Fig. S17), perhaps influenced by local lagoonal eddies and sediment supply. Association with prevailing currents was also evident for ASC in Guiana and Vietnam (Fromard et al. 2004; Nardin et al. 2016), in association with sedimentary bars. Some arcs of offshore R. stylosa colonisation were also evident in Kiribati (Ellison et al. 2017). Possible factors encouraging ASC include lagoon eddies and winds promoting geomorphic sediment deposits that provide shelter for the mangrove habitat to develop.

The mangrove shorelines of Jaluit Atoll show periods of accretion and erosion through the study period. Erosional processes were prevalent between 1945 and 1976 (Figs. S4, S6 and S12B) with DSAS results showing recession of the mangrove seaward edge along the lagoon shoreline. In this period, the major environmental disturbance to the atoll occurred with Typhoon Ophelia in 1958 (Blumenstock 1958), which caused greater than 5% reduction in the entire land area of the atoll (Ford and Kench 2016). High energy events are integral to the long-term geomorphology of atoll shorelines with generation of vast quantities of reef-derived sediment (Ford and Kench 2016; Kench et al. 2022), to supply and facilitate subsequent mangrove accretion and progradation. Even moderate climate events, such as tropical lows, are found to significantly influence island building and sediment supply with implications for mangrove expansion (Duvat et al. 2020). Following 1976, progradation results (Table 1) during rising sea-level (Fig. 5) indicate that accretion of sediment on the lagoon shorelines facilitated mangrove progradation (Fig. 6). Expansion of the mangrove seaward edge continued to be evident in the 2010/2011 and 2018/2019 satellite imagery analysed (Figs. S2, S6, S7B and S8B), at reduced rates (Fig. 6).

Results of trends of mangrove progradation (Table 1) indicate that sedimentation and accretion processes are outpacing rates of SLR (Fig. 5) as mangroves occupy tight elevation brackets between mean sea level and high tide levels (Ellison et al. 2022). Vulnerability assessment of adjacent reef health implied that enhanced sediment supply is not coming from reef mortality, with review showing that adjacent reefs are in good condition over the timeframe studied (Crameri and Ellison 2022). On-going monitoring, including substrate elevation and accretion research, and impacts of RSL rise and ENSO are ultimately vital to understand the future trajectory of change for atoll mangroves globally.

Progradation during RSL rise (Figs. 3 and 4) demonstrates combined mangrove biogeomorphic processes of both opportunistic colonization of biogenic carbonate sand and deterministic mangrove root accumulation (Ellison 2019). For future study on Jaluit, research to clarify progradation processes, sediment property analysis (McKee and Faulkner 2000; Ellison 2019) and accretion rate determination (Cahoon 2015) are needed. Low organic sediment and pollen concentration could indicate opportunistic colonisation, and high organic sediment with high pollen concentrations could indicate biogenic accretion (Ellison 2019).

Implications for Mangrove Planting and Management

Results of prevalent patterns in mangrove progradation (Fig. 4; Table 1) may be helpful for mangrove planting on atoll shorelines, which if successful can provide the coast with protection against flooding and erosion (Duarte et al. 2013). Such ecosystem-based adaptation integrates biodiversity conservation and ecosystem services (Grantham et al. 2011) and has become the preferred adaptation approach to climate change in least developed and developing countries (Nalau et al. 2018). Commendable efforts to plant mangrove hypocotyls and seedlings have resulted in some massive failures (Samson and Rollon 2008; Kodikara et al. 2017), such as over 70% of Philippines and 54% of Sri Lanka restoration sites resulting in complete mortality.

There is a wealth of expertise on mangrove planting methods (such as Moudingo et al. 2018; Asian Development Bank 2018; Melana et al. 2000), and some recommend patterns of seedling or propagule planting. The most commonly recommended pattern is grid patterns in rows spaced about 1 m apart (Fig. 7), which resembles LSA (Fig. 2B), as trialled by Gilman and Ellison (2007) in American Samoa.

For less calm sites, such as open lagoon settings with waves occurring at high tide, Asian Development Bank (2018: p21) and Melana et al. (2000: p52) advise planting propagules in an inverted V pattern, with the V point towards the sea, to deflect wave energy. If conditions are stronger, Asian Development Bank (2018, p 22) recommends cluster planting, both patterns resembling PE (Fig. 2C). These recommended planting patterns are illustrated in Fig. 7.

The greatest rates natural of expansion found of ASC (Table 1; Fig. 2A) have no matches with existing mangrove planting patterns (Fig. 7). Offshore sediment deposits from long-shore drift and local currents create areas of sediment accumulation that can provide protection from wave action. Patches of coloniser mangroves (Fig. 2C) also create lower energy conditions from wave and tide action similar to ASC, which may explain the faster rates of colonisation found compared to LSA (Table 1).

Different rates of expansion (Table 1) indicate that in the geomorphic context of low-lying atolls, restoration and ecosystem-based adaptation efforts may achieve greater results by tailoring patterns according to site conditions (Fig. 7). If time and funding are constrained, efforts could be best served by planting patches to replicate PE (Fig. 2C). If shorelines are protected from disturbance to allow natural seaward forest expansion (van Hespen et al. 2023), this would encourage shoreline advance through LSA. Whereas if maximum mangrove area recovery is desired with less limits on funding, then replication of the natural long-shore formation of sedimentary bars or spits resembling ASC could be trialled using offshore structures such as geotube or breakwaters, such as demonstrated from successful mangrove planting in Malaysia (Sulaiman and Mohidin 2018).

Results from Jaluit also show atoll mangrove shorelines protected with little disturbance will prograde naturally even during sea-level rise. The majority of transects measured across the 14.6 km of shoreline were found to be LSA (63% for linear regression rate and 64% for end point rate/net shoreline movement). Thus, this type of shoreline advance is responsible for a significant amount of the atoll's mangrove advance. Results from this study of mangrove progradation indicate conservation success on Jaluit, relative to extensive mangrove losses over the same timeframe elsewhere owing to direct human impacts (Giri et al. 2011; Goldberg et al. 2020; Richards et al. 2020). Successful protection of Jaluit's mangroves could be investigated to provide a case study how traditional resource use decision-making (Beger et al. 2008; Office of Environmental Planning Policy Coordination 2017), community-based conservation management plans (Baker et al. 2011; Sterling et al. 2017), and Ramsar Site designation have been effectively integrated.

Fig. 7 Mangrove planting patterns in practice, adapted to atoll shoreline settings



Conclusions

This analysis of atoll mangrove shoreline change supports concepts that atoll islands have current resilience in the face of climate change and associated SLR (Kench et al. 2018; Duvat 2019). While global trends for mangroves show continued losses owing to direct human impacts (Giri et al. 2011; Goldberg et al. 2020; Richards et al. 2020), this study shows that atoll shorelines with mangroves can be resilient during SLR, provided that direct human impacts are absent.

This study has found that high-resolution use of DSAS can quantitatively investigate mangrove progradation, showing prevalent patterns in seedling colonisation progress over time to become solid mangroves. The most frequent was linear shoreline advance, which resembles the most commonly used mangrove planting pattern of grid spacing of pneumatophores or seedlings. The second most frequent was offshore patch expansion, which resembles mangrove planting patterns recommended for more exposed sites, of V shapes or clusters. The greatest rates of shoreline seaward movement were, by contrast, found for arc-shaped colonisation, resembling spits, for which no equivalent mangrove planting pattern is evident, apart from use of offshore structures such as geotubes or breakwaters. Further understanding of conditions for successful mangrove progradation and ecosystem-based adaptation is essential to assist atoll communities manage threats posed by future increasing SLR.

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Data Availability Source ArcMap shapefiles, code and data are available from the authors on request.

Declarations

Competing Interests The authors declare no competing interests.

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